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Task-dependence of Activity/ Bite-force Relations and its Impact on Estimation of Chewing Force from EMG

ABSTRACT

Estimation of chewing force from electromyograms (EMGs) calibrated in isometric biting yielded strikingly high force values. We tested the hypothesis that EMG-based force predictions are excessive because of differing activity/bite-force relations in mastication and isometric biting. In nine patients, unilateral bite forces and EMGs of 4 elevator muscles were recorded during chewing and isometric clenching on a bite-fork. We estimated chewing force by substituting chewing EMGs of each muscle into isometric activity/bite-force regressions. The estimates were compared with actual chewing forces recorded by intra-oral transducers. In all muscles except the balancing-side masseter, the activity/bite-force ratio was significantly higher in chewing than in isometric biting. The actual mean chewing force amounted to 220 N, while EMG-based estimates ranged from 273 to 475 N, depending on the muscle used for estimation. The results indicate that different activity/force characteristics in dynamic and isometric biting can cause overestimation when chewing force is predicted from masticatory EMGs.

KEY WORDS: activity/bite-force relation, mastication, clenching, estimated chewing force.

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INTRODUCTION

Craniomandibular tissues are exposed to considerable forces during mastication. Since excessive loading could be involved in oral disease and material damage, simple means for the assessment of masticatory forces were sought. So that extensive incorporation of intra-oral sensors could be avoided, it was proposed that the chewing force be calculated from muscle activities calibrated in force units (Hagberg, 1987). In this method, EMGs and bite forces recorded during isometric clenching on a bite-fork were correlated by linear regression. The activity of a particular muscle obtained during mastication was then substituted for the EMG variable in the activity/bite-force regression. This procedure yielded surprisingly high force estimates of up to 600 N (Slagter *et al.*, 1993; Proeschel *et al.*, 1994; Tate *et al.*, 1994; Proeschel and Raum, 2001) that strongly exceeded chewing forces recorded by intra-oral transducers (Anderson and Picton, 1958; De Boever *et al.*, 1978; Lundgren and Laurell, 1986; Jäger *et al.*, 1989; Mericske-Stern *et al.*, 1992; Schindler *et al.*, 1998). Because of this discrepancy, the validity of the EMG-estimation method has been questioned, and possible limitations have been discussed in the studies cited above. However, until now, EMG-based force estimates have not been verified in comparison with actual occlusal loads on an intra-individual level. Validity of the EMG method requires as-yet-unestablished equal activity/bite-force relations in mastication and in isometric biting. Different working/balancing activity ratios in the two biting tasks (Proeschel and Raum, 2001) indicated a possible violation of this pre-condition. The present study therefore aimed to examine activity/bite-force relations in unilateral chewing and in isometric biting and to compare EMG-based force estimates with actually recorded masticatory loads.

MATERIALS & METHODS

Subjects

Nine patients (eight female, one male, mean age 52 ± 8 yrs) who had been treated with three-unit bridges supported by two ITI implants (Straumann, Waldenburg, Switzerland) volunteered for the study. All subjects gave informed consent to submit to the experimental protocol as approved by the ethics committee of our medical faculty.

The bridges covered the chewing center of one quadrant, starting from the first or second premolar. The restorations had been worn for 6 mos without complaints. None of the patients showed signs or symptoms of craniomandibular disorders.

Experimental Procedures

In each person, the original implant abutments were replaced by 2 abutments equipped with strain-gauges (Type FAE-02W-35-S6; BLH, Heilbronn, Germany). Experimental details are described in a previous paper (Morneburg and Proeschel, 2002). Briefly, 4 vertical rectangular walls were cut into each abutment at right angles. Each wall carried a strain gauge with the sensitive direction aligned along the abutment axis. The 2 strain gauges on opposing buccal and oral walls of each abutment were wired in line and constituted the resistance of a Wheatstone

quarter-bridge connected to a carrier frequency amplifier (TF19, Hellige, Freiburg, Germany). With this wiring, forces acting along the abutment axis were amplified, while horizontal force components could be widely suppressed. The mesiodistal pairs of strain gauges were not used for the present study. Duplicates of the patients' bridges were set onto the instrumented abutments. Electromyograms of right and left masseter and anterior temporalis muscles were recorded with the use of bipolar Ag/AgCl surface electrodes (Hellige) with 2-cm distance between electrodes. Prior to electrode attachment, the skin was cleaned with alcohol and rubbed with grinding paper for the reduction of impedance. The raw EMGs were filtered (from 10 to 5 KHz), full-wave-rectified, and root-mean-square-integrated with a 40-msec time constant (Digital EMG system 1500®, Disa, Denmark).

Measurement of Bite Force and EMG

In the mastication tasks, the patients chewed winegum unilaterally (Goldbären, Haribo, Bonn, Germany) on the side of the bridge. The EMG and force channels were scanned for 20 sec at a rate of 100 Hz by means of an A/D converter (6944A Multiprogrammer, Hewlett Packard, Palo Alto, CA, USA) controlled by a desktop computer (HP9826, Hewlett Packard, Palo Alto, CA, USA). The force signals arising from the 2 abutments were summed to give the total vertical chewing force acting on the bridge. This allowed us to measure the chewing force without leakage regardless of the site of force impact on the surface of the bridge (Morneburg and Proeschel, 2002).

For isometric biting, an electronic bite-fork (Proeschel and Raum, 2001) was inserted in place of the test food between the bridge and the antagonistic teeth. The patients clenched intermittently in a chewing-like rhythm, with peak loads alternating from low levels up to maximum bite force. For isometric contractions to be ensured, the teeth had to maintain steady contact with the bite-fork, which induced a jaw separation of about 6 mm. The electromyograms and the force signals of the bite-fork and the instrumented abutments were sampled and processed in the same way as in the chewing tasks. The force readings from the bite-fork and the instrumented bridges differed by less than ± 4%. For evaluation, only the bridge recordings were used. The bite-fork mainly served to simulate the experimental conditions of the previous studies in which muscle activities had been calibrated by subjects' clenching on the bite-fork only (Proeschel *et al.*, 1994; Proeschel and Raum, 2001).

Evaluation of Data and Statistics

The peaks of the unilateral bite force recorded in each chewing or clenching task were related to the peak activities of each muscle by linear regression. The strengths of the relationships were characterized by Pearson correlation coefficients (r-values). As an alternative measure for the relationship, we determined an activity/bite-force ratio by dividing the mean peak activity of each muscle by the mean peak force obtained in each chewing or clenching task. To test the validity of EMG-based force estimation, we substituted the mean peak chewing activity for A in the regression equation F = mA + b, determined from isometric bite-fork clenching. Since this was done for each muscle, 4 muscle-related estimates of the chewing force F were obtained in each subject. The estimates were compared with the mean peak chewing force measured by the instrumented bridges. Results are given as mean ± standard deviation in the text and as mean ± standard error in the graphs. Student's *t* test for paired data was applied for the examination of mean value differences for significance on the 1% level.

RESULTS

Relationships between Bite Force and Muscle Activities

In isometric clenching, the mean r-values of the 4 muscles ranged between 0.71± 0.24 and 0.85 ± 0.1. The mean r-values in mastication were significantly lower in each muscle and amounted to between 0.4 ± 0.2 and 0.49 ± 0.23. There were no significant differences between the r-values of different muscles in either of the 2 biting tasks. Some typical examples of the correlations are displayed in Fig. 1. The mean activity/bite-force ratios of the working-side masseter, the working-side temporalis, and the balancing-side temporalis were between 1.5 and 2 times higher in chewing than in clenching ($p < 0.01$) (Fig. 2). In contrast, the activity/bite-force ratio of the balancing-side masseter was not significantly different in the 2 biting tasks. The chewing activities exceeded the clenching activities in all muscles (Fig. 2). The working-side masseter activity in chewing was 2 times higher ($p < 0.01$) than in clenching, while the balancing-side activity was insignificantly enhanced by a factor of 1.2. The temporalis activities were enhanced by factors of 1.4 or 1.9, respectively ($p < 0.01$).

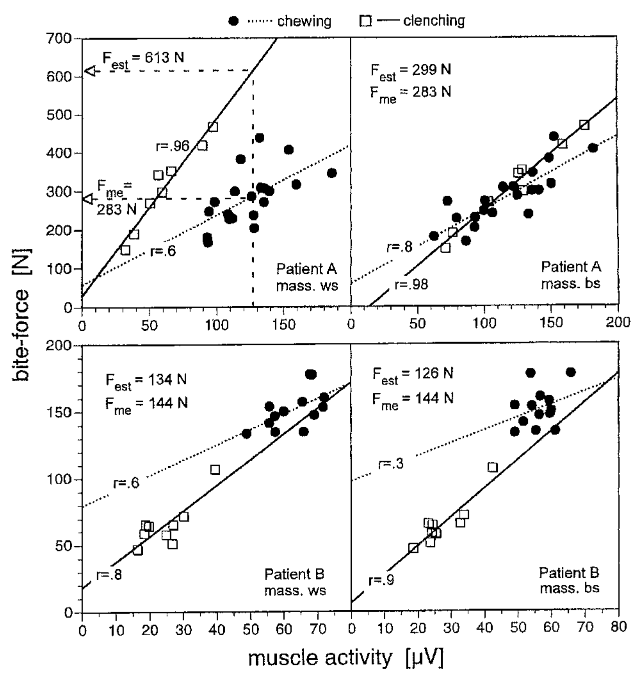

Figure 1. Examples of activity/bite-force relations in two selected patients with the activity used as the independent variable. F_{est} and F_{me} denote estimated and measured chewing forces. **Patient A:** Working-side masseter (mass. ws) showing a strong correlation in clenching on the bite-fork (r = 0.96) but a weak one in chewing (r = 0.6). The mean activity/bite-force ratio was higher in chewing (0.45 μV/N) than in clenching (0.23 μV/N), resulting in overestimation of chewing force (613 N) when the mean chewing activity (128 μV) was substituted into the activity/bite-force regression of clenching. Dashed arrows elucidate the estimation procedure. Balancing-side masseter (mass. bs) showed good correlations and almost equal activity/bite-force ratios (0.41 μV/N, 0.39 μV/N) in both biting tasks. Hence, the estimated chewing force deviated by only about 5% from the measured force. **Patient B:** Weak correlations in chewing because of missing small forces. However, in both muscles, activities *per* unit bite-force in the 2 biting tasks were similar, resulting in fairly correct force estimations.

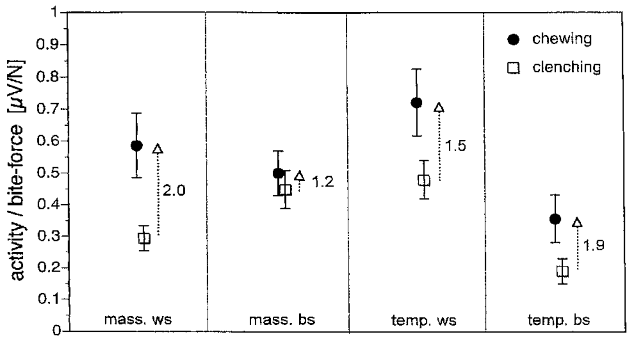

Figure 2. Group means and standard errors (N = 9) of activity/bite-force ratios for each muscle. Data next to the arrows indicate the factor by which the activity/bite-force ratio in chewing exceeded the activity/bite-force ratio in clenching. Since the bite-force cancels out, these factors also indicate the chewing/clenching ratios of the absolute activities. Abbreviations: mass = masseter, temp = temporalis, ws = working side, bs = balancing side.

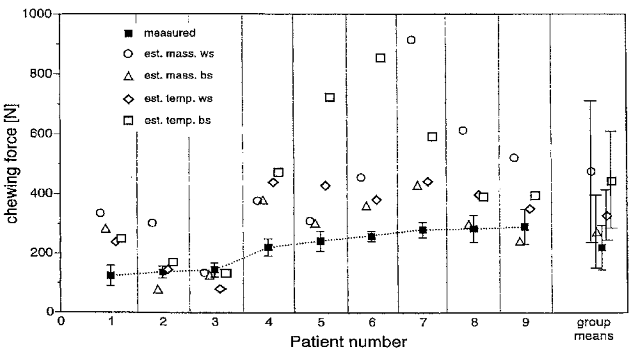

Figure 3. Actually measured masticatory forces with standard errors and forces estimated from the chewing activities of the 4 muscles in all subjects. Patients are arranged according to ascending values of measured forces (connected for the sake of clarity). The right-most compartment shows group means and standard errors (N = 9) of measured and estimated chewing forces. Patients #8 and #3 correspond to patient A and patient B of Fig. 1. Standard errors of measured forces are based on the number of chewing cycles performed during the recording period. The number of cycles varied interindividually between N = 12 and N = 32. Estimated forces have no error bars, because only one value could be obtained *per* patient and muscle. Abbreviations: est = estimated chewing force, mass = masseter, temp = temporalis, ws = working side, bs = balancing side.

EMG-based Force Estimates *vs.* Measured Forces

The actual loads acting on the bridges during chewing varied interindividually between 125 N and 290 N, with a group mean of 220 N ± 67 N (Fig. 3). The group mean of the clenching force amounted to 236 N ± 92 N. In eight patients, the clenching force was bigger than or equal to the chewing force. Only one rather cautious subject (Fig. 1, patient B; and Fig. 3, number 3) exerted a smaller force in clenching than in mastication. The EMG-based force estimates (Fig. 3) were, in most cases, considerably higher than the measured forces and depended on the muscle. A deviation of less than 15% between estimated and measured chewing forces was obtained from the activity of 5 muscles in three persons (numbers 2, 3, and 8). In one subject (Fig. 1, patient B; Fig. 3, number 3), the force estimates from 3 muscles coincided approximately with the measured chewing force. From working-side masseter activities, a group mean force of 475 N ± 248 N was estimated. A likewise high value of 442 N ± 245 N was obtained from the balancing-side temporalis activity. A more moderate prediction of 329 N ± 125 N resulted from the working-side temporalis. The balancing-side masseter provided 273 N ± 123 N, which came closest to the group mean of the actual chewing force of 220 N. Except for the balancing-side masseter, all differences between EMG-based force estimates and measured chewing forces were significant.

DISCUSSION

Because of the complicated experimental procedures, our study was confined to a relatively small number of cases. However, in view of the limited data on activity/bite-force relationships in human mastication (Ahlgren and Öwall, 1970), the results may provide some new information. The activity/bite-force relations in isometric clenching were weaker than those observed in dentate non-patient groups (Bakke *et al.*, 1989; Slagter *et al.*, 1993; Tate *et al.*, 1994; Proeschel and Raum, 2001). This may be due to stressful experimental conditions, such as artificial teeth and cables, that might have influenced neuromuscular control in the patients. The activity/bite-force relations in mastication were significantly weaker than in clenching. The correlation coefficients were similar to those reported by Ahlgren and Öwal but were smaller than r-values found in symmetric jaw closing against a simulated food resistance (Ottenhoff *et al.*, 1996). Weak correlations in mastication have been explained by activation of deeper muscle sections that are possibly not strongly correlated with the EMGs of the superficial portions (Hylander and Johnson, 1989). The tumbling bolus and various jaw-closing directions in mastication could perhaps trigger a random activation of such muscle portions. This may not apply to isometric biting, where the jaw and the bite-fork are at rest. A rather trivial cause for weak correlations was the lack of low chewing force peaks in some patients, which could lead to more or less horizontal regressions (Fig. 1, patient B). The weak activity/bite-force relations in chewing do not allow conclusions to be drawn concerning the quality of relations between activity and muscle forces (Hylander and Johnson, 1989). In contrast to the subjects of Ahlgren and Öwall, a few of our patients revealed quite good correlations, with r-values up to 0.85 (Fig. 1). Such stronger relationships were not common to all muscles but could appear together with weak correlations in the same person (Fig. 1, patient A).

With respect to the validity of EMG-based force estimates, the activity/bite-force ratios (Fig. 2) were more useful than the regression analysis. These ratios clearly showed that muscle activity associated with a certain bite force was considerably higher in chewing than in isometric biting. A similar observation was reported for sums of elevator muscle activities (Schindler *et al.*, 1998). Our study, in addition, revealed that the enhancement of activity *per* unit bite-force in chewing depended on the muscle and on its function as a working- or balancing-side elevator. The obvious task-dependence of activity/bite-force ratios violates the validity of masticatory-force-estimation from EMG, in particular when only 1 muscle is used in this procedure (Hagberg, 1987; Slagter *et al.*, 1993; Proeschel *et al.*, 1994; Tate *et al.*, 1994). If the respective muscle generates higher activity *per* unit bite-force in mastication than in isometric biting, the masticatory force will be overestimated when the chewing EMG is used in the isometric activity/bite-force regression. Just as illustrated in

patient A (Fig. 1), this caused the high number of excessive force estimates (Fig. 3). The different activity/bite-force ratios in the 2 motor tasks could reflect different activity/muscle-force relations as well as different combinations of muscle and reaction forces facilitated by the redundancy of the craniomandibular force system (Van Eijden *et al.*, 1990). In the latter case, a valid estimation of chewing force from EMG would require a three-dimensional force-model in which all involved muscle and reaction forces could be considered together (Hatcher *et al.*, 1986; Trainor *et al.*, 1995). Data provided by one of these models (Hatcher *et al.*, 1986) allow for a rough estimate of occlusal and temporomandibular joint loads based on the activities found in our patients: If muscle forces in chewing would be enhanced (with respect to clenching) by the same factors (chewing/clenching activity ratios in Fig. 2) as muscle activities, the chewing force derived from the cited model would exceed the clenching force by 30 to 40%. This would contradict our experimental finding of equal mean forces in both biting tasks. A hypothetical depressor counteraction could, in principle, reduce the masticatory force. However, compensation of bite-force by antagonistic co-activation was found only in isometric biting (Pruim *et al.*, 1978; Miles and Madigan, 1983) but not in chewing. These considerations indicate that increased muscle activities in chewing could hardly be associated with proportionately increased muscle forces. Rather, they imply task-dependent relations between muscle activities and muscle forces and thus between muscle activities and bite-forces. Higher muscle activities *per* unit bite-force were observed in biting with smaller jaw gapes than with bigger ones (Manns and Spreng, 1977; Lindauer *et al.*, 1993). Likewise, isotonic contractions of limb muscles are known to produce more activity than isometric contractions (Komi, 1973). Additional muscle activity was also evoked when the neuromuscular system could anticipate a counteracting force during jaw closing (Ottenhoff *et al.*, 1992). Such effects could be relevant, since opposing teeth approach a distance of about 0.5 mm in chewing (Proeschel and Raum, 2001) but remain separated by 6 mm in clenching on the bite-fork. Further, the contraction in chewing is partly non-isometric, and the neuromuscular system may anticipate the resistance of food during the closing movement. These features could possibly explain a general increase of muscle activity *per* unit bite-force in chewing. However, since no specific side preference could be assigned to the quoted effects, the asymmetric enhancement of the masseter EMGs remains puzzling. Side-related differences in activity/bite-force relations could be provoked by oblique bite-force directions (Van Eijden *et al.*, 1990; Mao and Osborn, 1994). The asymmetric increase of activity/bite-force ratios in our patients would roughly comply with activity/bite-force relations obtained for a medially directed bite-force in a previous study (Van Eijden *et al.*, 1990). Analysis of the present data, however, provides no information concerning the direction of peak force during chewing.

In summary, the prediction of chewing force from dynamic EMGs and isometric activity/bite-force relations usually resulted in considerable overestimation. The reason for this was that a certain bite-force in chewing was associated with higher muscle activity than the same bite-force in clenching. The surplus masticatory activity differed between muscles and was smallest for the balancing-side masseter. Biomechanical considerations suggest that the higher muscle activity in chewing was not associated with likewise higher muscle forces. This should be considered in all attempts to model occlusal or temporomandibular joint loads using EMG data obtained from chewing.

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